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CRUSTAL STRUCTURE OF THE ANDES FROM RAYLEIGH WAVE DISPERSION

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ABSTRACT

Records from a Benioff short-period seismograph located at Huancayo, Peru, are digitalized and then passed through a low-pass filter to get the long-period waves. In this way the dispersion curves of Rayleigh waves for paths along the Andes can be computed from seismograms which otherwise would be unusable. The comparison with the empirical curve for a "normal" continental crust (Press 1960) and with specially computed theoretical models indicates a crustal thickness of the order of 50 km. For periods between 20 and 25 sec., the observed group velocity shows abnormally low values.

Introduction

The crustal structure of the Andes has been studied by Aldrich and others (1958) using the seismic refraction technique in the regions close to Toquepala, Peru and Chuquicamata, Chile. In this work there is an indication of the two major discontinuities (Conrad and Mohorovičić) together with approximate values for the velocities within each layer, but the authors do not give a definitive estimate of the thickness of the crust.

The method based on dispersion of surface waves (Ewing, Jardetzky, and Press 1957, p. 196) can be used if the periods are long enough to provide information about a vertical section up to some 60 km. thick. A unique crustal model is not found in this way, but with the help of auxiliary data the ambiguity can be reduced. Recent papers which have used these techniques to demonstrate greater thickness under the mountains in the continents are those of Kovach (1959) and Savarensky and Sikharulidze (1959).

The records of a short period instrument are not useful for the study of long period waves because these are selectively rejected (Benioff 1932, fig. 7). Nevertheless these waves do exist in the seismograms, though masked by higher frequency trains. If the actual record is passed through a low pass filter, we may expect to regenerate some of the low frequency waves up to a limiting period where the instrumental attenuation is big enough to impede the distinction of signal from noise.

In the present study, we selected some of the seismograms recorded at Huancayo, Peru from a Benioff short-period vertical seismograph, and we calculated the curves of dispersion of Rayleigh waves for paths north and south of Huancayo and along the Andes (fig. 1). We used a digital low pass filter, and succeeded in recovering periods up to 45 seconds. This technique makes it possible to recover useful data from old seismograms. However, more precise results must await the installation of additional stations equipped with new instruments.

Filtering Technique

In a seismogram let x_n be the amplitude corresponding to the time $t = n\Delta t$, where the origin of times is arbitrary, Δt a given time interval, and n any integer.

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The operation $y_i = \sum_{-l}^{l} c_k \cdot x_{i+k}$ ($c_k = c_{-k}$ = real constant) is a transformation with frequency response

$$g(\omega) = c_0 + 2\sum_{1}^{l} c_k \cdot \cos(k\omega\Delta t)$$

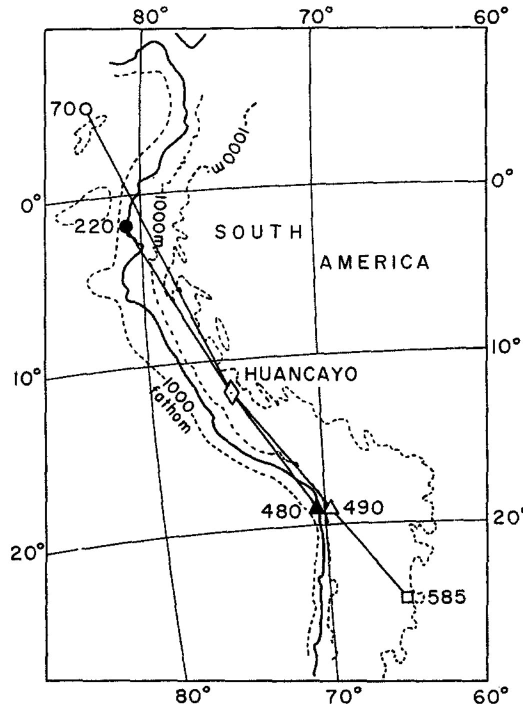

FIG. 1. Location of the earthquake epicenters and the Huancayo Station. The numbers are after Gutenberg and Richter (1954).

and no phase shift (Blackman and Tukey 1958). For $l = 10$, $\Delta t = 1$ sec. and $c_k = l - k$, the frequency response is

$$g(\omega) = \sin^2\left(\frac{l+1}{2}\,\omega\Delta t\right) \Big/ \sin\frac{2\omega\Delta t}{2}$$

which is shown in fig. 2. Thus this operation acts as a low-pass filter with a cutoff around $T = 19$ seconds.

We digitalized the Huancayo records, measuring amplitudes at one-second intervals. The digital filtering was carried out in the Bendix G-15 electronic computer of the Seismological Laboratory, and the smoothed values were plotted automatically by the plotter that is auxiliary to the computer. The time for the filtering plus plotting is less than 4 sec. per point. Fig. 3 shows a comparison between a filtered and unfiltered record.

In table I we show the data concerning the earthquakes that were analyzed. The shocks are numbered after Gutenberg and Richter (1954).

Experimental Group-Velocity

We followed the method described by Ewing, Jardetzky, and Press (1957, p. 198), to compute the group-velocity dispersion curves of Rayleigh waves. The

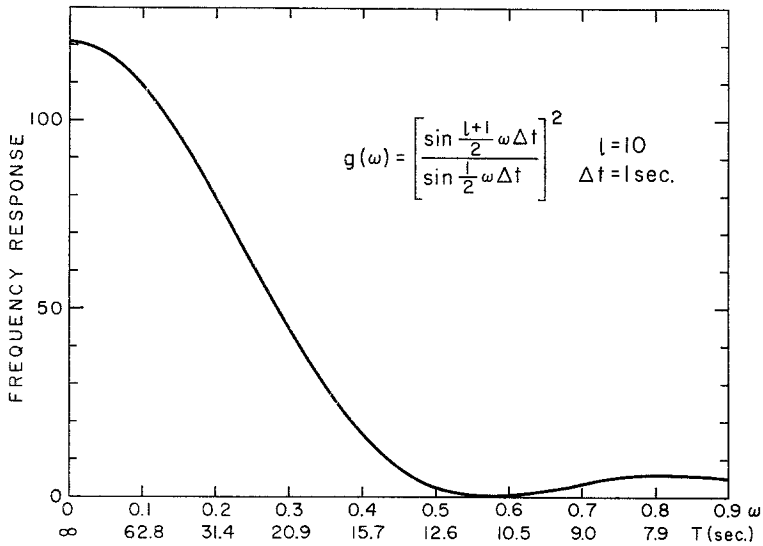

Fig. 2. Frequency response for the digital low-pass filter as a function of period.

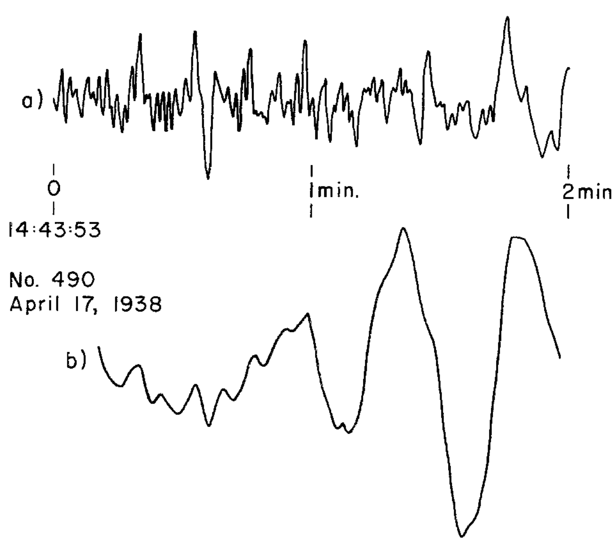

Fig. 3. Comparison between the recorded (a) and the filtered (b) seismograms for earthquake No. 490.

derivative of the curve of travel time against wave number was computed graphically.

For shock No. 70 the path was partially oceanic and a correction was made to take into account both refraction and the oceanic segment. For each period, a refracted path was calculated by using Snell's law and the corresponding oceanic and

TABLE I

No	Date	Origin time (GCT)	Epicenter	Mag.	Distance
70	March 5, 1943	00:31:40	5° N, 82.5° W	6.75	18.7°
220	October 3, 1933	10:21:25	2.1° S, 81.2° W	6.25	11.5
480	March 31, 1940	16:52:30	19° S, 70.5° W	6	8.7°
490	April 17, 1938	14:39:38	19° S, 69.5° W	6.5	8.7°
585	August 25, 1948	06:09:24	24.5° S, 65 W	7	16.0°

"normal" continental velocities (Ewing, Jardetzky, and Press 1957, pp. 171, 197). Then the time associated with the oceanic portion was subtracted from the total travel time. This corrected time and the continental portion of the earth were used to compute the group velocity.

The group-velocity data is shown in fig. 4, together with the "normal" continental curve (Press 1960). In general there is a decrease in velocity which indicates a crustal thickness larger than normal. In a following section these curves will be compared with other theoretical curves. For the path south of Huancayo there are consistently very low velocities in the period range 20–25 seconds.

Errors may be due mainly to uncertainties in the origin time of the shocks or in the location of the epicenters, since the distances are not more than 20°. But in the unfavorable case of systematic errors of ½° in all the epicenters the points in fig. 4 will remain significantly below the "normal" continental curve.

Experimental Phase Velocity

A knowledge of the phase-velocity curves may give a greater confidence in the results. Unfortunately none of the direct methods (Ewing and Press 1959, Aki 1960) to get them can be applied here since we have only one station.

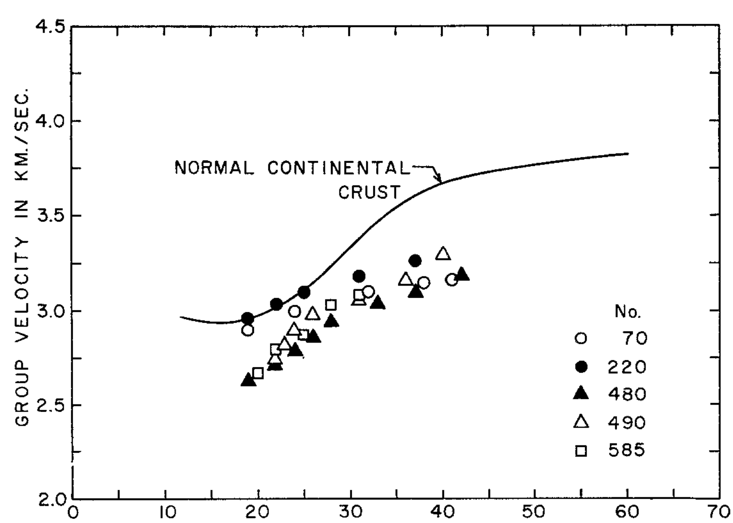

Fig. 4. Experimental group-velocity of Rayleigh waves. The "normal" curve is taken from Press (1960).

The method developed by Brune and others (1960) can be applied if the initial phase at the epicenter is known. This is possible in an explosion where the excitation can be considered to be a trough of vertical motion, the Fourier components having zero phase shift. In an earthquake this is not known *a priori*, and therefore there is an ambiguity that cannot be avoided until we have a better knowledge of the source. Nevertheless, we computed the curve, assuming integer or half-integer wave numbers at the origin. It was possible to eliminate all but a specific initial wave number by applying the criteria that the phase velocities have "reasonable" values. According to Brune and others (1960) the travel time of the peaks was cor-

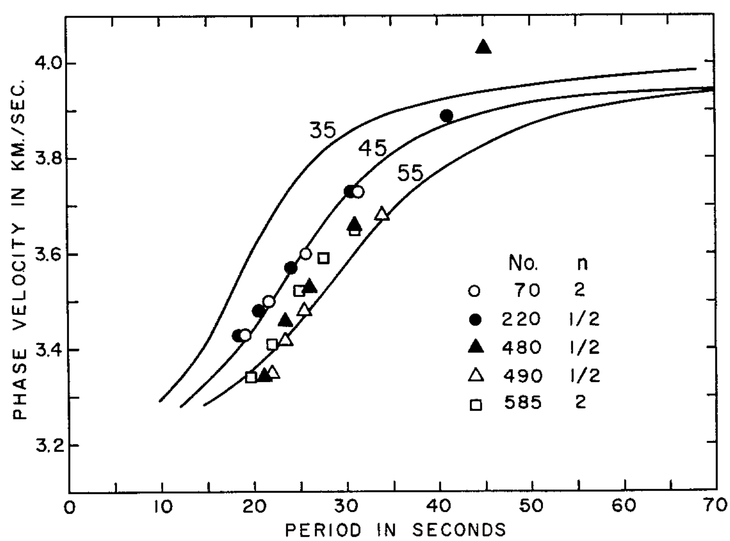

FIG. 5. Phase velocity of Rayleigh waves by Brune's method. n = initial phase number. The standard curves are taken from Press (1960).

rected for the instrumental delay by $T/4$ (T = period of the Fourier components) due to cylindrical spreading, and by nT (n an integer or half integer).

The instrumental delay was calculated from Benioff's formula (Benioff, 1932):

$$\Delta = \text{arc tan}\,\frac{(T/T_0)^2 - 1}{2T/T_0} - \text{arc tan}\,\frac{\epsilon_g T}{1 - (T/T_g)^2}$$

where: T = period of oscillation
T_0 = free period of the pendulum
T_g = free period of the galvanometer
ϵ_g = damping constant of the galvanometer
Δ = instrumental delay in radians.

The damping constant of the galvanometer was not known, but the delays were computed for critical damping (ϵ_g = 1.46) and for a certain overdamping (ϵ_g = 9.0). The maximum difference in delay correction was 4 sec. We took the average of the delays for both extreme cases, to have a possible error less than 2 seconds.

The phase-velocity data are presented in fig. 5 together with the "standard" curves of Press based on group velocity for a trans-African path. This is for rough comparison only. However the thickness agrees with the values found for group velocity to give a crust thicker than normal. Of course the data need to be corrected if the initial phase of these shocks can be found in some way in the future. Further special phase-velocity curves should be computed using auxiliary information for these regions.

Theoretical Models

Various models for the crust under mountain ranges have been studied by several authors (for a summary, see Gutenberg 1959, pp. 32 ff.). We calculated the dis-

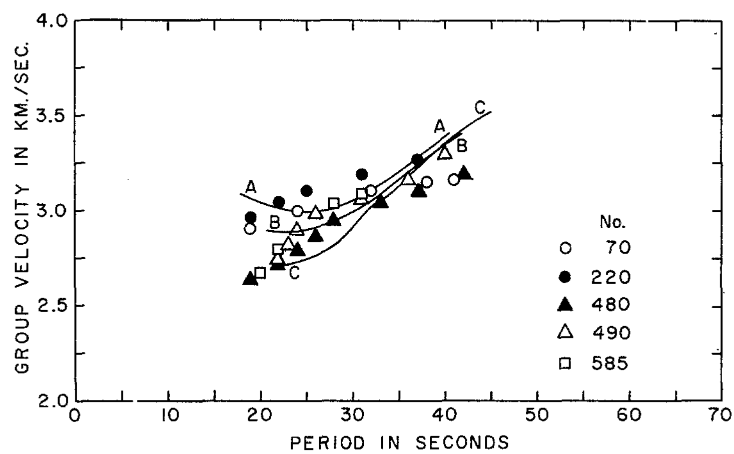

Fig. 6. Comparison between the empirical Rayleigh-wave velocities and models A, B and C. See Table II.

persion curves of Rayleigh waves for some of these models, using the program for the Bendix G-15 computer, based on the Haskell matrix method (Press 1960). In fig. 6, we include the empirical points and three theoretical curves that fit the data approximately. These correspond to variations of the model of Meyer and others (1960) and the model of Press for the Nevada region (Press 1960). The fit is fair for the variations of Press' model, and poor for the variation of the model of Meyer and others (1960) in which we have to assume rather high elastic constants. For the low computed group velocities south of Huancayo, none of the models gave a satisfactory fit.

Conclusions

1. Digital filtering makes it possible to use short-period instruments for dispersion studies of crustal structure. This enables us to use the large file of older records.

2. The Andes mountains possess a "root", the total thickness of the crust being of the order of 50 Km. This is consistent with gravity results in the Andes (Wuenschel 1953) which are compatible with the thicker crust.

3. The low velocities for the periods between 20 and 25 seconds and the path

south of Huancayo, have not been explained by the models assumed. Wuenschel (1953) found a negative gravity anomaly in that region, which he attributed to low density volcanic and continental sediments, based also in the geologic evidence. The top low-velocity layers in model C (fig. 6) didn't produce the fit we looked for, but we cannot rule out this possible explanation. More precise data should enable us to clear up this point and also give us in better detail the crustal structure of the Andes.

4. A simpler explanation is given by Phinney (1961), the low velocity branch would correspond to a "leaking mode." The irregularities of the base of the crust do not scatter these waves as much as they would waves close to grazing incidence, which form the high velocity branches of the dispersion curves.

TABLE II

Layer	Model A after Press (1960)				Model B after Press (1960)				Model C after Meyer and others (1960)			
	d km	α km/sec	β km/sec	ρ g/cm³	d km	α km/sec	β km/sec	ρ c/gm³	d km	α km/sec	β km/sec	ρ g/cm³
1	30	6.03	3.58	2.78	25	5.90	3.40	2.78	1.8	2.86	1.65	2.20
2	20	6.70	3.80	3.00	25	6.70	3.80	3.00	1.6	4.83	2.80	2.30
3	∞	7.96	4.60	3.37	∞	7.96	4.60	3.37	23.5	6.14	3.54	2.78
4									23.5	6.97	3.95	3.00
5									∞	8.28	4.78	3.37

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